

EXPRESS MAIL NO. ER054264345US

PATENT
Atty. Docket No. 02-4098

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE
APPLICATION FOR U.S. LETTERS PATENT

Title:

IMPROVED GEOPHONE

Inventor

James E. Barger

IMPROVED GEOPHONE

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR
DEVELOPMENT

[0001] This invention was made by an agency of the United States Government, or under contract with an agency of the United States Government. The name of the United States Government agency and the government contract number are: DARPA/SPO, Contract Number F33615-02-C-1262.

BACKGROUND OF THE INVENTION

[0002] **Field of the Invention.** This invention relates generally to improved geophones and other motion sensors. More specifically, this invention relates to a geophone or similar motion sensor that has improved coupling and is less sensitive to electrical noise.

[0003] **Related Art.** Typically, geophones comprise a heavy, rugged external case with a spike on the bottom that allows the geophone to be coupled to a reference surface, such as the ground. Within the external case is a mass that is relatively light with respect to the external case, sometimes referred to as a “proof mass.” The proof mass is commonly coupled to the external case by means of a relatively soft spring. Thus, the external case moves with the ground or reference surface, but the proof mass generally does not move with the external case. This creates a relative motion between the proof mass and the external case. This relative motion is detected because the external case is generally magnetized and there is a coil within the proof mass in which current is induced by the movement of the proof mass through the magnetic field. In a typical application, the voltage within the coil is proportional to the relative velocity between the external case and the proof mass. This voltage can then be processed in order to determine the relative velocity.

[0004] Because the geophone senses the relative motion between the external case and the proof mass, an important factor in ensuring accurate measurements by a geophone or other ground motion sensor is to ensure that there is a sufficiently high quality of coupling between the

geophone (and in particular, the external case) and the reference surface. It is desirable for the movement of the external case to track the movement of the reference surface as closely as possible.

[0005] Poor coupling can occur for various reasons. For example, when a geophone is disposed on the ground, the mass of the geophone and the compliant properties of the soil can affect the accuracy of motion measurements. This is because the top layer of the soil is influenced by the mass of the geophone and the motion of that layer with the geophone on top of it will differ from the movement of that layer in the absence of the geophone. Thus, the geophone will not accurately measure the motion of the reference surface, but only the motion of the reference surface as influenced by the geophone itself.

[0006] Because of these problems with coupling, many existing geophones cannot be deployed by simply throwing or dropping the device onto the ground or reference surface. In addition, most geophones are too delicate to maintain functionality when they are deployed in this way.

[0007] Thus, a need exists for a geophone or similar sensor that has improved coupling characteristics such that the geophone can be successfully deployed by simply throwing or dropping the geophone onto the reference surface. Moreover, it would be particularly desirable to have a geophone that is sufficiently rugged to maintain functionality after being deployed in this fashion. Finally, it would be desirable for such a geophone to have reduced electrical background noise such that it would be capable of detecting relatively weak ground motion signals.

SUMMARY OF THE INVENTION

[0008] An improved system for sensing ground motion is provided. The system generally comprises a shell, a case within the shell, and a suspension that connects the case and the shell. The mass of the case is greater than the mass of the shell, preferably by at least a factor of 2, and even more preferably by at least a factor of 10, or even greater. An electrode within the shell detects relative motion between the shell and the case. In one embodiment, the system is cylindrical in shape. The suspension between the shell and the case may comprise a closed cell foam that is preferably much stiffer in the radial direction than in the axial direction. Moreover,

a fluid may be disposed between the shell and the case. This fluid preferably serves both to provide damping to the system, and to increase the capacitance between the electrode and the case.

[0009] In another embodiment of the present invention, a shell, a case within the shell, and a suspension coupling the shell and the case are provided. Once again, the mass of the case is greater than the mass of the shell, preferably by at least a factor of 2 and even more preferably by at least a factor of 10, or even greater. In this embodiment, two electrodes are provided -- one attached to the shell and one attached to the case -- wherein the relative motion between the two electrodes produces a signal. In this embodiment, the overall system is preferably cylindrical with a cone-shaped nose end. The cone-shaped nose preferably enhances the ability of the sensor apparatus to penetrate the ground so that the device could be deployed by simply dropping it from a height.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] FIG. 1 depicts a cross-section of a sensor system according to an embodiment of the present invention.

[0011] FIG. 2 depicts a cross-section of a sensor system according to another embodiment of the present invention.

[0012] FIG. 3 depicts an electro-mechanical model of an embodiment of the present invention.

[0013] FIG. 4 depicts an amplifier circuit design according to an embodiment of the present invention.

[0014] FIG. 5 depicts an alternative amplifier circuit design according to an embodiment of the present invention.

[0015] FIGs. 6A-B depict the performance of various ground sensor systems.

[0016] FIG. 7A depicts a circuit diagram of a noise power spectral density model.

[0017] FIG. 7B depicts a diagram of noise power spectral density values.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0018] Reference will now be made to the present preferred embodiments of the invention, examples of which are illustrated in the accompanying drawings.

[0019] FIG. 1 shows a cross-section of an embodiment of an improved geophone or other similar sensor according to the present invention. As shown FIG. 1, a sensor system **101** comprises a substantially cylindrical shell **102** and a case **103** enclosed within shell **102**. Sensor system **101** is disposed on a reference surface **115**, which may be the ground. Shell **102** is preferably made from a light, tough material such as PVC. However, shell **102** may be made from a wide variety of materials that are preferably lighter than the material that makes up case **103**. In a preferred embodiment, case **103** is at least 2 times greater in mass than shell **102**, and even more preferably at least 10 times greater. In fact, as a general matter, the greater the mass difference between the case and the shell, the better the results that can be obtained using this invention. Case **103** is preferably made from tungsten. However, case **103** may be made from a variety of other materials, so long as it is heavier than shell **102**. Between shell **102** and case **103** is suspension **104**. Suspension **104** couples shell **102** to case **103** and is preferably a cylindrical jacket of closed-cell foam. In a preferred embodiment, this foam collar is about 100 times stiffer in the radial direction than in the axial direction. In FIG. 1, the radial direction is the horizontal direction, represented by dashed line **111**; the axial direction is the vertical direction, represented by dashed line **110**. The axial stiffness is adjusted so that the case **103** resonates in the axial direction at a desired low frequency cutoff.

[0020] The case **103** contains one or more batteries **105**, charge amplifiers **106** and/or signal conditioning circuits **107**. Metal foil electrodes **108** and **109** are fixed to the inside ends of shell **102**. These electrodes are used for electrostatic sensing of relative axial motion between them and the case **103**. The use of electrostatic signal transduction is preferred because it frees shell **102** from any transduction apparatus, apart from simply having a conducting surface. In this way, shell **102** needs only to function as a housing -- keeping the remainder of the system from the weather etc. This is contrary to conventional geophones, which use magnetic transduction that requires magnetic iron parts to be attached to the external shell, thereby increasing its weight.

[0021] Electrostatic signal transduction also provides the device of FIG. 1 with relatively low background noise. Charge amplifiers 106 are used to amplify motion-induced signals, which may use capacitors in the source and feedback positions of an operational amplifier. In such systems, the noise of capacitors is negligible. Moreover, capacitors shunt the few necessary resistors, effectively reducing their noise as well.

[0022] In a preferred embodiment, the space between shell 102 and case 103 is filled with a fluid which has a high relative dielectric coefficient (K) and viscosity, such as ethylene glycol. Essentially, the relative dielectric coefficient is a measure of the dielectric characteristic of a fluid relative to vacuum (which has a relative dielectric coefficient of 1). A preferred relative dielectric coefficient would be approximately 2 (i.e., twice that of vacuum), and a particularly preferred relative dielectric coefficient would be above 78 (the relative dielectric coefficient of water). A preferred viscosity would be above 1.0 centipoise (1.0 centipoise is the viscosity of water at room temperature), and a particularly preferred viscosity would be greater than 10.0 centipoise. This fluid serves both to increase the capacitance of the sensing electrodes and also to damp the relative motion.

[0023] The embodiment described in FIG. 1 takes advantage of the principle of minimum unsprung weight. This principle, which derives from automotive applications, suggests that minimum motion-induced forces between the ground and a vehicle resting on it will be achieved by reducing the weight of the portion of the vehicle resting on the ground. However, to the knowledge of the present applicant, all existing geophones violate this principle. Thus, as described above, currently existing geophones comprise relatively heavy external shells which contact the reference surface, and enclose a relatively light proof mass, which is coupled to the external shell by a spring with low stiffness.

[0024] The present invention, however, has reversed this common arrangement. Thus, as shown in FIG. 1 and described above, a very light external shell (such as shell 102 in FIG. 1) is in contact with a reference surface and is mechanically connected to a relatively heavy internal case (such as case 103 in FIG. 1) by a centering spring (such as suspension 104) that has a relatively high stiffness in all directions except in the direction of ground motion being sensed. In general, ground motion may be sensed in either the vertical direction, which measures the up and down

motion of the ground, or in the shear direction, which measures the side to side motion of the ground. The stiffness of the spring in the sensing direction is set to resonate with the internal case mass at the low frequency sensing cut off frequency. In this way, the heavy internal case is isolated from ground motion in the sensing direction at frequencies within the desired range, and the relative displacement between the external shell and internal case is equal to the ground motion displacement being sensed.

[0025] A second embodiment of the present invention is shown in cross-section in FIG. 2. The embodiment shown in FIG. 2 is particularly well-suited for ground penetration by high-speed impact, such that the device may be dropped from a relatively high distance. In other words, the embodiment shown in FIG. 2 is particularly well-suited for “self-coupling” to the reference surface. As used herein, “self-coupling” refers to the ability of the geophone to couple to the reference surface when it has simply been dropped onto the surface without the need for it to be specifically planted into the ground by a human operator.

[0026] As shown in FIG. 2, sensor apparatus **201** comprises generally cylindrical external shell **202** and an internal case **203**. As in the embodiment shown in FIG. 1, shell **202** is preferably constructed from a relatively light material such as PVC, while case **203** is preferably constructed from a relatively heavy material such as tungsten. Preferably, case **203** is at least 2-10 times heavier than shell **202**, or even greater. Moreover, shell **202** and case **203**, are coupled by means of a suspension **210**. In a preferred embodiment, the device is made as thin as possible to promote penetration into the ground or other reference surface. Thus, the radius of the shell is preferably less than its height. Moreover, shell **202** may be provided with a nose cone **205** to further promote ground penetration.

[0027] One or more batteries **204** may be provided in the nose cone **205** of shell **202** in order to provide momentum at impact. However, a damper, such as foam **206** should be provided in nose cone **205** in order to isolate the mass of the batteries **204** to prevent their mass from affecting the dynamic shell mass.

[0028] Further, overlapping sensor electrodes **207** and **208** are attached to the inside wall of shell **202** and the outside wall of case **203** respectively. Relative axial motion (up and down) between the shell **202** and case **203** causes the degree of electrode overlap to change. This method of

sensing relative motion is preferred in this embodiment to placing electrodes at the ends of the shell **202** (see, e.g., electrodes **108** and **109** in FIG. 1). This is because, with the minimized diameter of the shell **202**, the capacitance of the end spaces will be low relative to electronic stray capacitance, and could cause some inaccuracies in measurements.

[0029] The space between shell **202** and case **203** is preferably filled with a fluid such as ethylene glycol to increase capacitance and to help damp out the initial impact. Moreover, one or more orifice rings **209** may be placed at the ends of case **203** to provide high fluid flow resistance at the large relative velocities of impact, but negligible resistance at the low signal relative velocities.

[0030] Finally, a radio **211** may be provided at the end of shell **202** opposite the nose cone **205**. Radio **211** is preferably connected to the remainder of sensor apparatus **201** by means of a wire **212**. Thus, when sensor apparatus **201** is disposed onto a reference surface, such as the earth's surface, and penetrates that surface, radio **211** is captured by the surface and is pulled free.

[0031] FIG. 3 represents an electro-mechanical circuit model of a preferred embodiment of the present invention in operation. The shell of mass M_{shell} (represented as inductor **301**) rests on earth moving with velocity v_o (represented as current source **302**) and having stiffness k_{ground} (represented as capacitor **303**) and resistance R_{ground} (represented as resistor **304**). The shell velocity is v_1 , and it is reduced from the ground velocity by relative velocity between ground and shell $v_o - v_1$. It is preferable to minimize this "slip" velocity. The relative velocity between the shell (such as shell **102** of FIG. 1) and inside case (such as case **103** of FIG. 1) is $v_1 - v_2$. This is the velocity that appears across the sensor plates. The mechanical to electrical transduction ratio is equal to the sensor capacitance (C_o , represented by capacitor **308**) multiplied by the bias voltage across the sensor plates (v_{bias}), divided by the gap between the plates ($d + x$). As would be evident to one skilled in the art from the electro-mechanical circuit, maximizing signal output voltage **309** requires that the shell mass (inductor **301**) must be small and that the resonance frequency of the case mass (represented by inductor **305**) and the damping spring (represented by resistor **306** and capacitor **307**) must be lower than the signal frequency.

[0032] Now will be described in more detail a signal amplification system according to an embodiment of the present invention. In general, the signal source impedance of a preferred

embodiment is capacitive, so that a charge amplifier (such as charge amplifier **106** in FIG. 1) will provide signal gain with the least noise addition. There are two preferred configurations. First, the sensor plates can be located at the amplifier source. Second, the sensor plates could be located in the feedback path.

[0033] The feedback path alternative is shown in FIG. 4. This arrangement makes the output voltage linear with the sensor plate separation. In general, in a particular system, there is a “static gap” between the sensor plates. For example, in FIG. 1, in a resting position, there is a certain gap between the case **103** and each electrode **108** or **109**. This static gap may be represented by d . The additional distance between case **103** and each electrode **108** or **109** caused by the motion of the ground is x , and is referred to as a “signal gap.” In general, d is much greater than x . Because static gap is much larger than the signal gap, this means that there is a large offset voltage on which the small signal voltage rides. If the bias voltage is steady (a battery), the offset voltage will not appear, because the amplifier **405** has no static gain, thereby solving the offset problem. The output voltage is proportional to the bias voltage, the ratio of fixed to sensor capacitances, and the ratio of signal displacement to gap. Thus, output voltage is given by the formula:

$$V_0 = V_{bias} \frac{C_f}{C_{eff}} \left(1 + \frac{x}{d} \right)$$

[0034] where V_{bias} (**401**) is the DC voltage bias used to offset the voltage from the static gap and C_f (**402**) is a fixed capacitance to be chosen by a system designer. C_{eff} , the effective capacitance created by the gap (static and signal) between the sensor plates, is given by the formula:

$$C_{eff} = C_0 \left(1 - \frac{i}{\omega C_0 R_e} \right)$$

[0035] where ω is frequency and R_e (**403**) is the resistance in the feedback path. C_0 (**404**) is the capacitance of the plates, given by the standard formula for capacitance:

$$C_0 = \frac{\epsilon_0 K_e A}{d}$$

[0036] where ϵ_0 is permittivity, K_e is the relative dielectric coefficient of the fluid between the sensor plates, A is the area of the sensor plates, and d is the distance between the sensor plates. In general, a roll-off frequency occurs when $\omega C_0 R_e$ is approximately equal to 1. In such cases, output voltage may be given by:

$$V_o(f) = V_{bias} \frac{C_f}{C_0} \frac{x(f)}{d}$$

[0037] The requirement of a bias voltage in this arrangement may cause problems in certain applications. In a practical system, there is a certain maximum amount of voltage that the amplifier can handle. Because of the requirement of a bias voltage in this arrangement, the amount of gain that the amplifier can apply is limited. This is because the use of the bias voltage limits the amount of gain. An alternative system that eliminates this problem is shown in FIG. 5.

[0038] In the amplifier option shown in FIG. 5, the two capacitor positions (C_0 (502) and C_f (501)) are reversed from their positions in FIG. 4. In this configuration, there is no offset proportional to the static gap, and the output voltage is the same as with the other configuration, except with the two capacitors reversed. The equation for output voltage is given by:

$$V_o(f) = V_{bias} \frac{C_0}{C_{eff}} \frac{x(f)}{d}$$

[0039] In this configuration, because there is no DC offset proportional to the static gap, the bias signal can be a high frequency carrier signal, rather than in the previous case where the bias had to be DC. This has the advantage of lower amplifier noise. However, the output signal must be amplitude demodulated to get the data signal. Various amplitude modulation techniques are known to those skilled in the art.

[0040] Now will be described in more detail the signal processing aspects of a preferred embodiment of the present invention, particularly as related to suspension "sag." In general, the rest position of an inner case according to an embodiment of the present invention (such as case 103 in FIG. 1) will change somewhat when the sensor is reoriented. This is because of sagging in the suspension spring. The offset capacitance caused by this gap and the distance of the sag is given by:

[0041]

 $C_o = K_e \epsilon_o A/d$, and

[0042]

 $x_o = g/\omega_o^2$

[0043] where g is gravitational acceleration. Following these equations, the maximum sag (x_o) is 1.7 mm when the axis is vertical and the suspension system resonance frequency (ω_o) is 12 Hz. In a system such as that described with respect to FIG. 1, the result of this sag is to increase the spacing between case 103 and the upper electrode 108. This decreases the sensitivity of the signal produced by the electrode 108. At the same time, the distance between case 103 and lower electrode 109 is decreased. To minimize the impact of this case offset problem, the outputs of the two charge amplifiers associated with the two electrodes are subtracted. The following formula represents this

subtraction:

$$V_{left} - V_{right} = V_{bias} \frac{C_0}{C_f} \frac{x}{d + x_0} - V_{bias} \frac{C_0}{C_f} \frac{-x}{d - x_0} = V_{bias} \frac{C_0}{C_f} \frac{2xd}{d^2 - x_0^2} = 2V_{bias} \frac{C_0}{C_f} \frac{x}{d} \left(1 + \left(\frac{x_0}{d} \right)^2 + \left(\frac{x_0}{d} \right)^4 + \dots \right)$$

[0044] The difference between the two is twice the signal voltage of either one, with a small correction for the sag-induced difference in the two gaps. For a static gap (d) of 5 mm, for example, the maximum sensitivity increase is a factor of 1.13, or 1 dB.

[0045] Signal sensitivity is also an important aspect of a preferred embodiment of the present invention. Two signal sensitivity curves are shown in FIGs. 6A-B. These curves show the displacement sensitivity (in millivolts per angstrom) of two geophones as a function of frequency. These curves were calculated using the differential equations implicit in the electro-mechanical network shown in FIG. 3 (with the equations used to calculate soil stiffness (k_{ground}) and resistance (R_{ground}) taken from F.E. Richart *et al.*, Vibrations of Soils and Foundations, Prentice-Hall, Englewood Cliffs, N.J. 1970, the entirety of which is hereby incorporated herein by reference). The parameters used to calculate the curve in FIG. 6A are listed below:

[0046] Mass of Shell = 8 g

[0047] Mass of Case = 80 g

[0048] Diameter of Cylinder = 25 mm

[0049] Cut-off Frequency = 12 Hz

[0050] Static Gap = 5 mm

[0051] Quality Factor = 1

[0052] Ground Density = 1800 kg/m³

[0053] Speed of Shear Wave in Ground = 20 m/s

[0054] Poisson's Ratio of Ground = 0.25

[0055] $C_f = 400 C_o$

[0056] $V_{bias} = 200 V$

[0057] $C_o = 33 pF$

[0058] $R_e = 400 M\Omega$

[0059] The geophone parameters listed above are representative of a preferred embodiment of the present invention. For the curve in FIG. 6B, the geophone parameters used were that of the commercially available HS-1 geophone (manufactured by GeoSpace Corporation).

[0060] The ground parameters used are representative of soft sand and are the same for both curves.

[0061] The curves in FIGs. 6A-B were calculated for a constant (in frequency) value of ground velocity v_o . The low-frequency cutoff frequency was 12 Hz in both cases. The curve FIG. 6A shows that at and above 12 Hz the sensor output is independent of frequency (as is the ground vibration) out to a frequency of about 800 Hz. This means that there is no slippage between the shell and the ground at frequencies lower than 800 Hz. In other words, the shell is perfectly coupled to the sand.

[0062] Curve 6B shows that the sensor output is independent of frequency (as is the ground vibration) only to about 40 Hz. The peak in the curve at about 70 Hz represents the mass of the

HS-1 resonating with the ground stiffness. In other words, the shell is perfectly coupled to the sand only in a narrow frequency band. Moreover, the sensor output cuts off at about 90 Hz. It would be necessary to attach the HS-1 to a stake in the sand to end this slippage between its shell and the sand. (In both curves, the solid line is the measurement for ground motion in the vertical (up and down) direction; the dashed line is the measurement for ground motion in the horizontal (side to side direction)).

[0063] This comparison demonstrates the significance of reducing the weight of the external shell, as taught and described herein.

[0064] In addition to increasing the ground motion sensitivity, the embodiments of the present invention may also result in decreased noise over conventional geophones.

[0065] Sensor noise for a charge amplifier in the configuration shown in FIG. 4 may be calculated using standard equations provided by the amplifier manufacturer. In this embodiment, the amplifier chosen for the calculation is a Burr-Brown (TI OPA655) low-noise operational amplifier. FIG. 7A shows a circuit diagram of a model for testing noise power spectral density. This is the same as FIG. 4 except for the addition of 3 noise generators as specified by the amplifier manufacturer.

[0066] The first noise source is the thermal noise spectrum of the resistor, denoted by V_{RE} . It is calculated as usual as $\sqrt{4RkT}$, where R is resistance of the resistor, k is the Boltzman constant, and T is the absolute temperature. The second noise source is the input current noise spectrum denoted by I_{NI} . The manufacturer gives this number as $1 \text{ fA}/\sqrt{\text{Hz}}$ at $f < 1 \text{ kHz}$. The third noise source is input voltage noise spectrum is denoted by V_{NI} and the manufacturer gives this number as $20 \text{ nV}/\sqrt{\text{Hz}}$ at 100 Hz.

[0067] FIG. 7B shows a diagram of the sensor noise power spectral densities calculated based on the following set of input parameters:

[0068] $V_{NI} (100 \text{ Hz}) = 2 \text{nV}/\sqrt{\text{Hz}}$

[0069] $I_{NI} (f < 1 \text{ kHz}) = 1 \text{ fA}/\sqrt{\text{Hz}}$

[0070] $V_{Re} = \sqrt{(4kTRe)}$

[0071] $G = C_f/C_o$

[0072] $R_e = 4 * 108 \Omega$

[0073] $C_o = 33 \text{ pF}$

[0074] $4kT = 1.6 * 10^{-20}$ at 20 deg. C

[0075] FIG. 7B shows plots of the sensor noise power spectral densities for displacement (pm/ $\sqrt{\text{Hz}}$) (curve 750), velocity (nm/s/ $\sqrt{\text{Hz}}$) (curve 751), and acceleration ($\mu\text{g}/\sqrt{\text{Hz}}$) (curve 752) for the preferred embodiment of the present invention described above. The curves of FIG. 7B were calculated from the equations implicit in the circuit diagram shown in FIG. 7A together with the noise parameters described above. FIG. 7B demonstrates that a geophone according to the present invention is quieter than other geophones.

[0076] For example, with respect to noise related to velocity measurements, also plotted on FIG. 7B (with the symbol 'G' at 753) is the measured velocity noise power spectral density value for the HS-1 geophone at the specific frequency of 100 Hz (data was not readily available for other frequencies). As can be seen in FIG. 7B, a comparison of the value of the velocity sensor noise power spectral density curve 751 at 100 HZ (point 754) with the measured velocity noise 753 reveals that the former is quieter by a factor of two at this frequency.

[0077] Also plotted on FIG. 7B (with the symbol 'A' at 755) is the measured acceleration noise power spectral density value for the Wilcoxon 731A accelerometer at 100 Hz (data was not readily available for other frequencies). Once again, the acceleration sensor noise power spectral density value (756) of an embodiment of the present invention is quieter by a factor of two at 100 Hz.

[0078] Also plotted on FIG. 7B (curve 757) is the acceleration noise power spectral density representing the lowest vertical seismic accelerations ever measured, according to the USGS "Low-Noise Model." Acceleration noise (curve 752) of an embodiment according to the present invention is comparable to this, indicating that noise is as low as practically necessary.

[0079] Thus, the noise output of the present invention is lower than other geophones for both velocity and acceleration measurements, and is comparable to the lowest seismic acceleration ever measured.

[0080] Although particular embodiments of the invention have been described and illustrated herein, it is recognized that modifications and variations may readily occur to those skilled in the art and consequently it is intended that the claims be interpreted to cover such modifications and equivalents.